WA Science—Journal of the Royal Society of Western Australia, 97: 97–109, 2014

Geochronology of the Archean of Western Australia: a historical perspective

R T PIDGEON [1*] & M T D WINGATE [2]

[1] *Western Australian School of Mines, Curtin University, Kent Street, Bentley, WA 6102, Australia.*

[2] *Geological Survey of Western Australia, 100 Plain Street, East Perth, WA 6004, Australia.*

* *Corresponding author* ✉ *r.pidgeon@curtin.edu.au*

The Yilgarn and Pilbara Cratons of Western Australia are amongst the largest segments of Archean crust on Earth. Unraveling the geological history hidden in these ancient rocks has been a major challenge, involving many years of geological fieldwork, geochemical and geophysical studies and, most significantly, the application of isotopic dating. In this contribution we present a brief overview of the role of isotopic dating in providing numerical measurements of the geological age of igneous and metamorphic events and resolving key questions on the evolution of the cratons. Our review begins with the building of the first mass spectrometer in the Physics Department at the University of Western Australia in the 1950s. We follow the rapid evolution of techniques and concepts of isotopic dating up to the present day when the integration of accumulated geochronological data provides a high-resolution record of Archean events in the Yilgarn and Pilbara Cratons. We highlight major achievements, including the identification of the oldest fragments of the Earth's crust in metasedimentary rocks of the Yilgarn Craton and the determination of the age of the world's oldest fossils in the Pilbara Craton. Isotopic dating and associated isotope geochemistry have increasing roles to play in resolving problems of crustal evolution and deep crustal structure in the Archean cratons of Western Australia.

KEYWORDS: Archean, geochronology history, isotopic dating, Pilbara Craton, Western Australia, Yilgarn Craton.

INTRODUCTION

The geology of Western Australia is dominated by two Archean cratons, the Pilbara in the north and the Yilgarn in the south (Figure 1), overlain by volcanosedimentary basins and surrounded and separated by Proterozoic orogenic belts. The two cratons are amongst the largest segments of Archean crust on Earth and are immensely important as a store of economic mineral deposits and for their unique preservation of early life and Hadean and Archean geological history. However, unraveling the geological history of the cratons is extremely challenging, especially in the Yilgarn Craton, where outcrop is scarce, deep weathering is common, and the correlation of non-contiguous greenstone and sedimentary units or igneous bodies is uncertain. This challenge has been largely met by the application of isotopic dating and isotope geochemistry. For example, Wyche *et al.* (2012) stated that '...of particular significance is the accumulating body of geochronological and isotope data that has allowed the major periods of crustal growth in the Yilgarn Craton to be identified'. A similar comment can be made for the Pilbara Craton. The story of isotopic dating is one of evolving technical advancement coupled with new concepts and applications, many of which were developed and tested on problems from the Archean of Western Australia. It is, therefore, most appropriate that a paper on the evolution of geochronological knowledge on the Archean of Western Australia is part of this centennial volume.

The present review follows in the footsteps of earlier historical reports on the contribution of isotopic dating to studies of the Archean rocks of Western Australia. Wilson *et al.* (1960) reviewed data from Peter Jeffery's laboratory at the University of Western Australia (UWA), and were the first to recognise the widespread occurrence of ~2700 Ma granitic rocks in the southwest of Western Australia. Compston & Arriens (1968) and Arriens (1971) summarised new K–Ar and Rb–Sr age determinations on Australian Precambrian rocks up until 1967, recognising at this early stage the contrast between the 3000–2900 Ma ages in the Pilbara Craton and the 2700–2600 Ma ages that predominate in the Yilgarn Craton. De Laeter & Trendall (1979) described the early history of geochronology from the discovery of radioactivity, the development of mass spectrometry from Aston to Nier, the early evolution of the U–Pb, K–Ar and Rb–Sr techniques, to the construction of the first mass spectrometer in Western Australia in the Physics Department at UWA. A further review in this journal by De Laeter (1994), on the occasion of receiving the Royal Society Medal for 1993, continued the theme of geochronology of the early Earth and described some highlights of research on the Archean of Western Australia since 1979, including the discovery of >4 Ga zircons in quartzites of the Narryer Terrane (Froude *et al.* 1983). Particularly valuable are his comments on early geochronological research at the Western Australian Institute of Technology (WAIT, later to become Curtin University) and the early history of Peter Jeffery's laboratory at UWA. Each of these reviews is exceptional in conveying the experiences of individuals involved in leading geochronological research at that time.

In this review, we briefly summarise material covered in earlier reviews and follow the history of geochronological research on the Archean of Western

---

Australia up to the present day. A useful introduction to methods and concepts is provided by Kirkland & Wingate (2013). Photographs of some of the geochronologists who have made valuable contributions to the geochronology of the Archean of Western Australia are included in Figures 2 and 3. However, the proliferation of U–Pb zircon data in support of projects by the Geological Survey of Western Australia (GSWA) and Geoscience Australia (GA), the introduction of new dating and isotope technologies, and the wide range of contributions from Australian and overseas laboratories has made a comprehensive review impossible to achieve within the limitations of this article and we regret that some valuable contributions may not be accorded the recognition they deserve.

MILESTONES IN GEOCHRONOLOGY OF THE ARCHEAN OF WESTERN AUSTRALIA

Peter Jeffery's laboratory in the Department of Physics, UWA

In the early 1950s, little was known of the ages of geological events in the Yilgarn and Pilbara Cratons. Isotopic dating methods using thermal ionisation mass spectrometry (TIMS) were only just being developed in several laboratories in the USA [eg Rb–Sr (Aldrich *et al.* 1953); K-Ar (Wasserburg 1954); U–Pb (Tilton *et al.* 1955)]. Inspired by the potential of these new developments, Peter Jeffery, together with PhD student David Greenhalgh, assembled a Nier-type solid-source mass spectrometer, provided through a grant from the Department of Terrestrial Magnetism of the Carnegie Institution in Washington, in the basement of the Physics Building at UWA for the purpose of isotopic dating (Greenhalgh & Jeffery 1959). They were joined by William Compston, Glen Riley, and soon after, by John De Laeter, in pioneering research into the timing of geological events in the development of the Yilgarn and Pilbara Cratons.

Rb–Sr whole-rock dating

An important factor in the early success of the physics group from UWA was the collaboration with Alan Wilson from the UWA Geology Department. With Wilson to guide them in the field, the group undertook Rb–Sr dating of granites from the Darling Range Batholith in the hills to the east of Perth. Their discovery that the Rb–Sr age of a granite could be determined from a number of 'whole-rock' samples was a milestone in Rb–Sr geochronology (Compston & Jeffery 1959; Compston *et al.* 1960) and a major influence on geochronological studies of the Archean of Western Australia for 30 years. Their age of 2700 Ma for the granite at Canning Dam was the first precise age of a granite from the Yilgarn Craton. In 1960, Alan Wilson left UWA to take up the Chair of Geology at the University of Queensland and in 1964, Glen Riley took a position at the Australian Atomic Energy Commission at Lucas Heights. Bill Compston, who was by then on the UWA Physics staff, relocated to Canberra, to establish a Rb–Sr laboratory in the Department of Geophysics and Geochemistry at the Australian National University (ANU). These staff movements resulted in the disbanding of the UWA geochronology group. Jeffery concentrated his further research on nuclear astrophysics and no geochronological measurements were made in Western Australia for almost a decade, although Compston continued Rb–Sr isotopic dating at ANU.

Isotopic dating at the Australian National University (ANU)

In 1961, Compston and his group at the ANU converted a Metropolitan–Vickers MS2 gas-source mass spectrometer to a solid-source instrument for Rb–Sr dating. In an early PhD study, Turek (1966) demonstrated that gold mineralisation at Coolgardie, Kalgoorlie and Norseman defined a Rb–Sr total-rock isochron of 2400 ± 40 Ma. Pieter Arriens, a PhD graduate from UWA, joined Compston and undertook a wide-ranging Rb–Sr whole-rock study of granites from the Yilgarn and Pilbara Cratons. A review of geochronological knowledge of the Yilgarn and Pilbara Cratons up to that time was presented at the 1967 International Conference of Precambrian stratified rocks in Edmonton (Compston & Arriens 1968). In addition to Rb–Sr dating, Virginia Oversby from ANU reported Pb–Pb isochron ages of 2760–2630 Ma, using K-feldspar–plagioclase–total-rock samples, for eight intrusive bodies in the Kalgoorlie–Norseman area in the Yilgarn Craton (Oversby 1975).

In 1980 Malcolm McCulloch established a Sm–Nd laboratory at the ANU and applied the technique to dating Archean gneisses in the Yilgarn Craton (McCulloch *et al.* 1983 a, b). The success of Hamilton *et al.* (1979) in using the Sm–Nd whole-rock method to date Archean greenstones in South Africa raised the possibility that this technique could be used to date mafic rocks, a long-standing problem in geochronology. Dating the Archean greenstones of the Yilgarn Craton was the immediate challenge and McCulloch & Compston (1981) determined an isochron age of 2790 ± 30 Ma for the Kambalda greenstone sequence and also concluded, from the high initial ^{143}Nd/^{144}Nd, that the mantle had been highly depleted by the late Archean. However, Claoué-Long *et al.* (1984) questioned the McCulloch & Compston (1981) result for including associated sodic granites and a felsic porphyry in the isochron calculation and reported a re-determined Sm–Nd isochron age of 3262 ± 44 Ma for whole-rock samples of mafic–ultramafic lavas from the Kambalda area. This latter age was very controversial as it contradicted Pb isotope evidence suggesting the age of the lavas was close to 2700 Ma (Roddick 1984). This was finally resolved by a SHRIMP U–Pb age of 2692 ± 2 Ma on pyroclastic zircons from a chert unit within the greenstone sequence (Claoué-Long *et al.* 1988). The old whole-rock Sm–Nd date of Claoué-Long *et al.* (1984) was seen to be the product of mixing of unrelated rock components raising general questions on the application of the technique as a precise dating tool.

Dirk Nieuwland continued to operate the conventional U–Pb zircon laboratory and reported U–Pb zircon ages of ~3250 Ma for gneisses from the Toodyay district (Nieuwland & Compston 1981). In a rare application of K–Ar dating to Archean rocks of Western Australian, Wijbrans & McDougall (1987) reported ^{40}Ar–^{39}Ar ages of 2900–2840 Ma for metamorphic amphiboles from the eastern Pilbara Craton and interpreted them as indicating prolonged high temperatures within the Shaw Batholith or else dating a later thermal pulse associated with the intrusion of post-tectonic granitoids.

Alec Trendall arrives at the Geological Survey of Western Australia (GSWA)

The appointment of Alec Trendall from the Geological Survey of Uganda to the position of petrologist at GSWA in 1962 was arguably the next milestone in the development of geochronology in Western Australia. Trendall had been mapping Archean rocks in Uganda and realised the necessity of having accurate geochronological data for understanding Archean geology. On the advice of Peter Jeffery, he began a long-term cooperation with Compston at the ANU on Rb–Sr dating of rocks from the Archean of Western Australia. With the start-up of isotopic dating at WAIT in 1968, Trendall initiated a program of Rb–Sr dating between geologists from the GSWA and the De Laeter group at WAIT. During his long career at GSWA, where he served as Director from 1980 to 1986, Trendall remained a tireless advocate of geochronology.

Development of Thermal Ionization Mass Spectrometry (TIMS) at WAIT

The next important development in Archean geochronology was the appointment in 1968 of John De Laeter, a former student of Peter Jeffery, to head the newly established Physics Department at the Western Australian Institute of Technology (WAIT). One of his first actions was to purchase a 12 inch radius, MS12 solid-source mass spectrometer and build a Rb–Sr dating laboratory. Later that year he formed a close working relationship with Alec Trendall, where GSWA field geologists submitted samples of Archean rocks from the Yilgarn and Pilbara for Rb–Sr dating (Muhling & De Laeter 1971; De Laeter *et al.* 1975, 1981b; De Laeter & Baxter 1987).

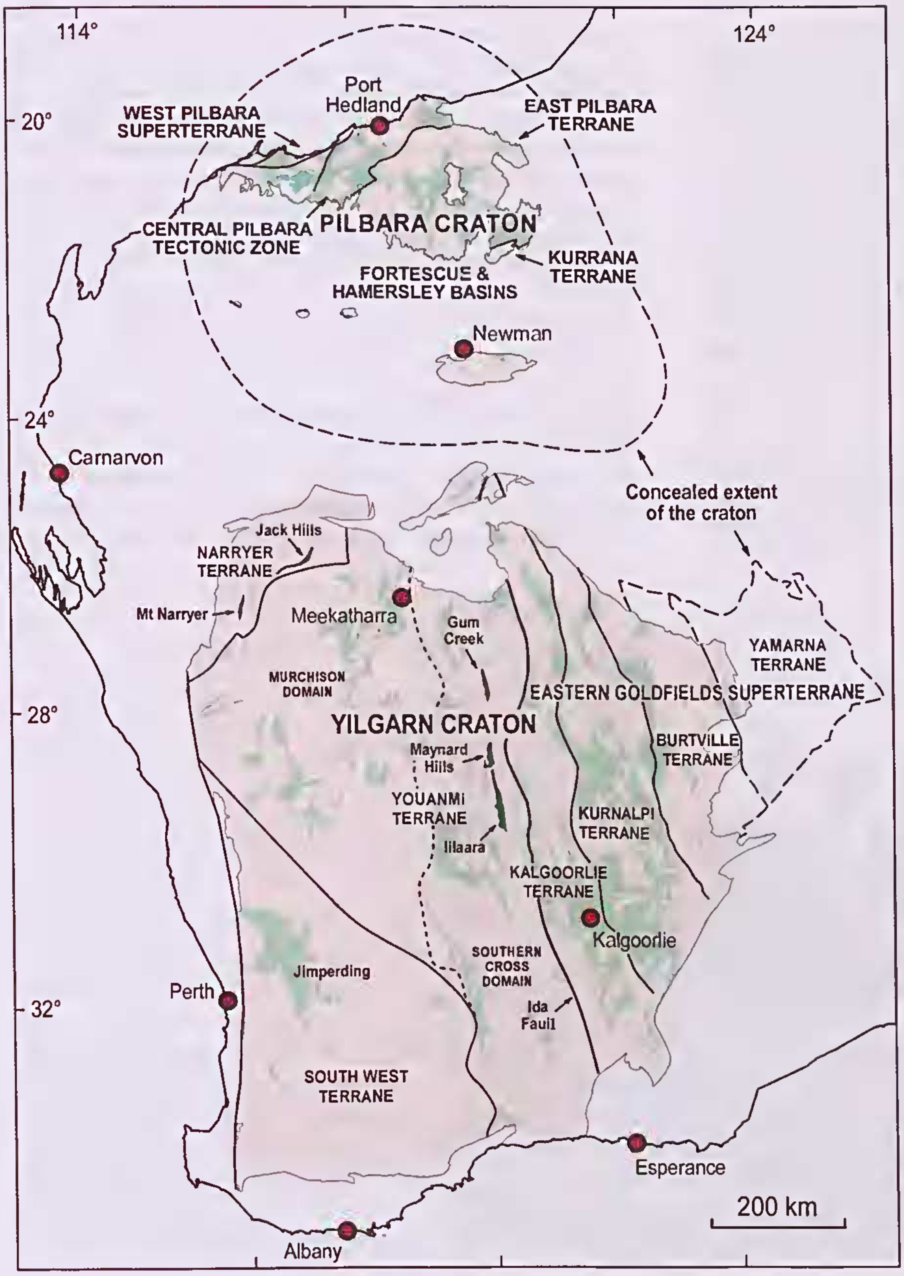

Figure 1 The Archean Yilgarn and Pilbara Cratons of Western Australia, and their terrane subdivisions (Yilgarn: Cassidy *et al.* 2006; Pawley *et al.* 2012; Pilbara: Hickman & Van Kranendonk 2012a, b). Localities shown include the Jack Hills and Mt Narryer, the Jimperding metamorphic belt, and the Gum Creek, Illaara, and Maynard Hills greenstone belts. Revised extent of the Pilbara Craton is from Hickman & Smithies, in prep.

Pb–Pb geochronology at the University of Western Australia (UWA)

In another landmark development in 1978, Hazel Chapman, with Michael Bickle and Neal McNaughton, set up a Pb–Pb laboratory at the Department of Geology at UWA. Samples were prepared at UWA and mass spectrometry was undertaken at WAIT. Pb–Pb studies included the report of a ~2700 Ma age for gneisses from the Diemals area north of Southern Cross (McNaughton & Bickle 1987). The group also studied the Pb–Pb geochronology of granite plutons in the Pilbara Craton (Bickle *et al.* 1989). Bickle and Chapman returned to the UK late in 1982, leaving McNaughton to carry on the laboratory within the Key Centre for Strategic Mineral Deposits headed by David Groves. Research focused on investigating the ages and origin of Yilgarn mineralisation (McNaughton & Cassidy 1990; McNaughton & Groves 1996) and included results of student theses (Perring & McNaughton 1990, 1992).

Sm–Nd and zircon U–Pb dating at WAIT

In 1978, Ian Fletcher joined the WAIT group as a research fellow on an ARC grant to Kevin Rosman and Alec Trendall to establish a Sm–Nd dating laboratory. Projects included a number of Sm–Nd model-age traverses across the Yilgarn Craton (Fletcher & Rosman 1984; Fletcher *et al.* 1983, 1985). In a landmark paper, De Laeter *et al.* (1981a) reported a 3348 ± 43 Ma Rb–Sr whole-rock age, supported by Sm–Nd age results, for banded gneisses near Mt Narryer in the northwest Yilgarn Craton, identifying the Narryer region as a uniquely old part of the Yilgarn Craton. De Laeter *et al.* (1985) reported Sm–Nd T_{CHUR} model ages of ~3.7 Ga for the Meeberrie Gneiss in the Mt Narryer area and ~3.54 Ga for a sheet of Dugel Gneiss within the Meeberrie Gneiss.

In 1982, Robert Pidgeon joined the WAIT group and set up a conventional TIMS U–Pb laboratory for zircon geochronology. Research in collaboration with Simon Wilde, who had recently joined WAIT from the GSWA, focused on greenstone belts in the western Yilgarn Craton, including the Saddleback and Wongan Hills belts, and identified two ages of greenstone volcanism—at ~3000 and ~2700 Ma—in the Youanmi and South West Terranes of the Yilgarn Craton (Wilde & Pidgeon 1986; Pidgeon *et al.* 1990).

Advent of SHRIMP at the ANU

The inability of first-generation ion microprobes to resolve Pb isotopes from unwanted molecular interferences in lunar samples led Compston, together with his former student S W Clement, to initiate a project in the early 1970s to build a high-resolution ion microprobe at the ANU Research School of Earth Sciences (Clement *et al.* 1977). The instrument, known as the Sensitive High Resolution Ion Microprobe (SHRIMP), had a working mass resolution of over 5000 and could easily resolve the isotopes of Pb from most isobaric interferences. This instrument was revolutionary in that static analyses could be made on 10–20 μm diameter spots on selected parts of zircon crystals, allowing inherited and disturbed parts to be avoided and leading to uncomplicated age determinations. Also, the speed of analysis meant that a large number of zircons could be analysed in a short time. With this new capability, it became possible to determine the distribution of detrital zircon ages in sedimentary samples, a task impractical using slow conventional TIMS techniques. Ireland *et al.* (2008) provided a comprehensive history of the development of SHRIMP I, from 1975 to 1980, and its commissioning in 1983. This instrument was to fundamentally change U–Pb zircon geochronology worldwide.

Hadean zircons discovered at Mt Narryer and the Jack Hills

The first project undertaken using the SHRIMP I ion microprobe was an investigation of the ages of detrital zircons in a conglomerate from Mt Narryer (Figure 1), an

Figure 2 Geochronologists in 1987 on the outcrop of Jack Hills metaconglomerate sample W74, which contains zircons with ages in excess of 4.0 Ga. From left to right: M T McCulloch, D R Nelson, W Compston, R T Pidgeon, I R Fletcher, S A Wilde and I S Williams.

area in the northwestern corner of the Yilgarn Craton already known to be extremely old from the Rb–Sr results of De Laeter *et al* (1981a, 1985). Samples were provided by Ian Williams and John Myers of the GSWA. The amazing discovery of a small number of zircon grains with ages greater than 4 Ga (Froude *et al.* 1983) focused worldwide attention on this area of the Yilgarn Craton and demonstrated the unique analytical capacity of the SHRIMP.

In the 1980s, Robert Pidgeon from WAIT and later Neal McNaughton from UWA took Archean zircon samples to Canberra for analysis on the SHRIMP. An important result of this research was the discovery of detrital zircons with ages >4.2 Ga in a quartz-pebble conglomerate from the Jack Hills (Figures 1, 2) (Compston & Pidgeon 1986) confirming the earlier results from Mt Narryer and extending the distribution of very old zircons. At the time, the reality of the old ages was questioned in the literature and doubts were raised about the integrity of the new SHRIMP (Schärer & Allegre 1985). However, these doubts were put to rest by reports of >4 Ga ages for Jack Hills zircons determined by single-zircon Pb-evaporation by Kober *et al.* (1989) of the University of Heidelberg in Germany, and by TIMS U–Pb analysis by Amelin (1998), then at the Royal Ontario Museum. The discovery of ancient zircons at Jack Hills foreshadowed extensive studies of the old grains by isotope and geochemical techniques, because these grains were the only known surviving fragments of the Hadean period of Earth's history (De Laeter & Trendall 2002; Wilde & Spaggiari 2007).

Geochronological research then focused on the old gneisses surrounding the conglomerates in an attempt to locate the parent rocks of the >4 Ga zircons. Kinny *et al.* (1988) from the ANU reported SHRIMP U–Pb zircon ages of 3678 ± 6 Ma for the monzogranitic Meeberrie Gneiss (Myers & Williams 1985), 3381 ± 22 Ma for the leucosyenogranitic Dugel Gneiss, and 3730 ± 6 Ma for meta-anorthosite of the Manfred Complex. Fletcher *et al.* (1988) reported a Sm–Nd, Pb–Pb, and Rb–Sr age of ~3.69 Ga for the Manfred Complex. Nutman *et al.* (1991) from the ANU reported the results of a comprehensive SHRIMP U–Pb study of zircons from the Narryer Gneiss Complex including an age of 3731 ± 4 Ma for a tonalite of the Meeberrie Gneiss. Kinny & Nutman (1996) emphasised that it is impossible to quote a single age for the Meeberrie Gneiss in the Mt Narryer region as it is a polyphase migmatite that has been metamorphosed to granulite facies, with ages ranging from 3730 to 3300 Ma. Nutman *et al.* (1993) used U–Pb zircon geochronology and Nd isotope geochemistry to map gneiss units of different ages in the Narryer Gneiss Complex, recognising a ~100 km wide tract of 3700–3300 Ma gneisses, flanked by 3000–2900 Ma gneisses, and all intruded by 2750–2620 Ma granites. Granites from near the Jack Hills showed complex zircon U–Pb systems but recorded age peaks at 3.75–3.65, 3.50 and 3.3 Ga (Pidgeon & Wilde 1998).

Research has continued on the old zircons from Mt Narryer and the Jack Hills using a variety of isotopic and chemical techniques, and the list of publications is too great to be covered in detail in this short overview. Maas & McCulloch (1991) investigated the U–Pb age, Nd isotopes, and REE chemistry of Jack Hills zircons and concluded they originated within a felsic parent rock. A notable contribution was that of Crowley *et al.* (2005) who made an ICPMS U–Pb age study of zircons from several outcrops of metaconglomerate and quartzite in the Jack Hills and Mt Narryer area and identified different trends in the age spectra which bear on the provenance of the zircons. Research groups from the University of Wisconsin, in association with Simon Wilde from Curtin University, and University of California, Los Angeles, in association with Robert Pidgeon of Curtin University, identified isotopically-heavy oxygen in the >4 Ga zircons and interpreted this as evidence for the existence of oceans on Earth ~4.3 Ga years ago (Wilde *et al.* 2001; Peck *et al.* 2001; Mojzsis *et al.* 2001; Valley *et al.* 2002; Cavosie *et al.* 2005).

SHRIMP II installed at Curtin University

A major landmark in the ongoing geochronological investigation of the Yilgarn and Pilbara Cratons was the initiative by John De Laeter to form a consortium comprising Curtin, GSWA and UWA, for the purpose of purchasing the first commercial SHRIMP instrument, SHRIMP II. University and GSWA funding was supplemented by a large equipment grant from the Australian Research Council. The SHRIMP II was installed at Curtin University in 1993 and Allen Kennedy was appointed as manager of the SHRIMP facility (De Laeter & Kennedy 1998). A second SHRIMP was installed at Curtin in 2003 under the umbrella of the Federal Government's Systemic Infrastructure Initiative, with support from the Government of Western Australia. With these instruments, zircon U–Pb geochronological research into the Archean of Western Australia accelerated rapidly.

SHRIMP U–Pb dating at GSWA

Another landmark decision that greatly enhanced geochronological research in the Yilgarn and Pilbara Cratons was the 1989 appointment of a geochronologist, Ian Fletcher, at GSWA to support its field program. He utilised primarily the Sm–Nd technique. However, as partners in the new SHRIMP, U–Pb zircon geochronology became a prominent tool at GSWA, and David Nelson, a recent graduate from the ANU, was appointed as the GSWA geochronologist in 1990, following Ian's departure.

GSWA has published an annual compilation of SHRIMP geochronological results since 1995. The first report, Nelson (1995), described results obtained in 1994, and included 26 SHRIMP U–Pb zircon analyses on felsic intrusive and extrusive rocks of the Eastern Goldfields. Nelson (1997a) reported SHRIMP measurements on 35 zircon samples, which revealed that felsic volcanic rocks were erupted in the southern part of the Eastern Goldfields between 2713 and 2672 Ma and were intruded by coeval granite sheets. Between 1995 and 2005, GSWA published more than 400 Geochronology Records that describe results for Archean samples dated by David Nelson.

An exceptional discovery made in this period was the presence of >4.0 Ga zircon xenocrysts in two late Archean granites from the Narryer Terrane and the Murchison Province (Nelson 1996, 1997c). The core of xenocrystic grain 11 from the ~2636 Ma granitic gneiss at Churla Well in the Narryer Terrane produced a ^{207}Pb/^{206}Pb age of

4183 ± 6 Ma (Nelson *et al.* 2000). The significance of this discovery in terms of the source rocks of the ancient zircons and of early crustal processes has not been resolved.

Also in this period, SHRIMP measurements of detrital zircons from quartzitic metasedimentary rocks in the Gum Creek, Maynard Hills and Illaara greenstone belts of the Southern Cross Domain (Figure 1) identified new sources of >4 Ga zircons (Wyche *et al.* 2004; Nelson 2005; Thern & Nelson 2012). Although it was previously thought that the ancient zircons were confined to the Narryer Terrane, these new discoveries extended the range of >4 Ga zircons to metasedimentary rocks in the centre of the Yilgarn Craton.

Nelson left GSWA in 2004 and was replaced by Curtin PhD graduate Simon Bodorkos. He was joined in August 2005 by Michael Wingate, a PhD graduate from the SHRIMP group at the ANU, then employed at the Tectonics Special Research Centre at UWA. Bodorkos left GSWA in 2007 to continue geochronology at Geoscience Australia, and Chris Kirkland joined GSWA as a geochronologist in 2008. Kirkland also brought experience in using isotopes such as Lu–Hf and Sm–Nd to explore crustal evolution. Wingate and Kirkland have expanded GSWA's extremely successful geochronology program; the Survey has so far published about 1150 Geochronology Records (mainly SHRIMP U–Pb zircon ages of individual rock samples), of which slightly more than half represent Archean rocks of the Yilgarn and Pilbara Cratons.

Ongoing isotopic dating of the Yilgarn Craton

In further studies, Nemchin & Pidgeon (1997) reported SHRIMP U–Pb zircon results for the Darling Range granites, concluding that they were emplaced between 2648 and 2626 Ma, and showing that the zircons contained 2690–2650 Ma cores. Schiøtte & Campbell (1996), at the ANU, reported zircon ages of 2716–2696 Ma for granites within greenstone belts in the Mt Magnet area and 2710 and 2694–2640 Ma for external granites. Wiedenbeck & Watkins (1993) reported similar ages of 2641 ± 5 and 2602 ± 14 Ma for post-folding granites from the same region. The ages of volcanism in the Murchison Domain, at 2.76–2.72 Ga (Pidgeon & Hallberg 2000), are comparable with zircon ages of ~2.73 Ga for felsic volcanic rocks from the Marda Complex (Pidgeon & Wilde 1990), but are marginally older than the ~2.71–2.67 Ga volcanic activity in the Eastern Goldfields (Nelson 1997b). The 1998 PhD thesis of Qi Wang at ANU provided an extensive dataset of new geochronological results for Archean granites and volcanic rocks, mainly from the Murchison and Southern Cross Domains (Wang 1998).

Between 2000 and 2008, several university–government projects generated an impressive amount of geochronology data for the Yilgarn Craton. Fifty-two ages were published for Archean rocks as part of the Norseman–Wiluna Synthesis Project, a collaboration between Geoscience Australia (GA) and UWA aimed at providing geochronological constraints on geodynamic and tectonic models for the Eastern Goldfields (Fletcher *et al.* 2001; Dunphy *et al.* 2003). Another comprehensive research project, funded by the Minerals and Energy Research Institute of Western Australia (MERIWA), on the characterisation and metallogenic significance of Archean granitoids, included U–Pb zircon and titanite ages, and Sm–Nd and Pb–Pb results, for 60 granites across the Yilgarn Craton (Fletcher & McNaughton 2002). GA published U–Pb zircon results for 14 granites in the Eastern Goldfields and 13 in the South West Terrane (Sircombe *et al.* 2007). Kositcin *et al.* (2008) reported the results of a project funded by the Australian Minerals Industry Research Association (AMIRA), including 35 U–Pb zircon ages for metavolcanic and metasedimentary rocks in the Eastern Goldfields.

Zircon provenance studies

The ability of the SHRIMP ion microprobe to conduct a large number of U–Pb zircon analyses in a short time

Figure 3 Geochronologists in 2013 in the SHRIMP laboratory at Curtin University. From left to right: P D Kinny, M T D Wingate, A I S Kemp, N J McNaughton and C L Kirkland.

(~15 minutes per analysis) has opened the way for provenance studies based on surveys of the age distribution of detrital zircons. This is best illustrated by the studies of the zircons in quartzites from Mt Narryer (Froude *et al.* 1983; Crowley *et al.* 2005; Pidgeon & Nemchin 2006) and the Jack Hills (Dunn *et al.* 2005) (Figure 1). These studies demonstrated that detrital zircons in these samples consist of two main age components: a main group with ages between 3.7 and 3.0 Ga and a subordinate group with ages between 4.37 and 3.9 Ga. SHRIMP provenance studies of detrital zircon suites from quartzites from elsewhere in the Yilgarn Craton (Kinny 1990; Bosch *et al.* 1996; Pidgeon *et al.* 2010) found that the quartzites of the Jimperding Metasedimentary Belt (Figure 1), which resemble quartzites of the Narryer Terrane, contain detrital zircons with ages between 3.8 and 3.0 Ga, but none older than 4 Ga, suggesting that the source rocks of the ancient zircons were not present in the provenance of the Jimperding sediments.

Early geochronology of the Pilbara Craton

Early research in the Pilbara Craton (Figure 1) was constrained by its remoteness and the lack of detailed geological maps, until publication of the GSWA mapping, starting with Hickman & Lipple (1975). The earliest determination of an Archean age for the Pilbara Craton was a ^{207}Pb/^{206}Pb age of 2790 ± 25 Ma for tanteuxenite from Woodstock, determined in the mass spectrometry laboratory at UWA (Greenhalgh & Jeffery 1959). An early outcome of close relationships developed between the Bureau of Mineral Resources (now GA), GSWA, and the ANU was the report by Leggo *et al* (1965) of Rb–Sr whole-rock ages of ~3000 Ma for a granite and felsic volcanic rocks from the Pilbara Craton. As a result of the cooperation between the WAIT group and GSWA, De Laeter & Trendall (1970) reported a Rb–Sr whole-rock isochron date of 2880 ± 66 Ma for the Copper Hills Porphyry. De Laeter and Blockley (1972) reported a Rb–Sr whole-rock isochron age of 3125 ± 366 Ma for foliated granitic gneiss near Marble Bar and 2670 ± 95 Ma for the Moolyella Monzogranite. They concluded from the initial ^{87}Sr/^{86}Sr that the granitic gneiss was close to primary crustal material whereas the Moolyella Monzogranite consists of reworked material. De Laeter *et al.* (1975) reported a well defined Rb–Sr whole-rock isochron age of 2951 ± 83 Ma for gneissic granite from the Shaw Granitic Complex and 2606 ± 128 Ma for the Cooglegong Monzogranite which intrudes the batholith.

In 1974, Virginia Oversby at the ANU undertook a program of research on common-Pb mineral systems and reported Pb–Pb data for whole-rock and feldspar samples from gneissic granites along the Mt Newman railway line, which showed that primary ages of granite domes were in the order of 2950 Ma, whereas a number of the samples showed signs of secondary disturbance (Oversby 1976).

Old age of the Big Stubby lead

The first evidence of an exceptionally old age for the Warrawoona Group of the Pilbara Craton was the report by Sangster & Brook (1977) of the isotopic composition of Pb from the Big Stubby deposit in the Duffer Formation near Marble Bar. They found that this Pb has the most primitive isotopic composition of any conformable Pb and estimated its age at ~3500 Ma from the Stacey–Kramers Pb-evolution model (Stacey & Kramers 1975). In 1977, Pidgeon established an isotope dilution TIMS U–Pb laboratory at the Research School of Earth Sciences at the ANU and published a zircon age of 3452 ± 16 Ma for dacite of the Duffer Formation within the Warrawoona Group (Pidgeon 1978a), recently mapped by Hickman & Lipple (1975). This result confirmed the antiquity of the Warrawoona Group indicated by the Pb composition of the Big Stubby deposit (Sangster & Brook 1977) and was the first precise age determined on the volcanic succession of the Warrawoona Group. Further Pb isotope studies of galena by Richards *et al.* (1981) corroborated the primitive isotopic compositions of the Pilbara conformable leads.

Dating of granites and greenstones in the Pilbara

Geochronological research continued on the Pilbara granites. The first age determination on the Mt Edgar Granitic Complex was the 2670 ± 95 Ma Rb–Sr isochron age for the Moolyella Monzogranite (De Laeter & Blockley 1972). Compston & Arriens (1968) used 12 samples of the Mt Edgar Granitic Complex to obtain a Rb–Sr age of ~3050 Ma; this was later recalculated by De Laeter to 3279 ± 169 Ma (Hickman 1983). Pidgeon (1978b) reported a U–Pb zircon age of 3280 ± 20 Ma for a granodiorite sample from this batholith. Williams & Collins (1990) reported SHRIMP U–Pb zircon ages of ~3440 Ma for the oldest gneissic part of the Mt Edgar Granitic Complex and ~3310 Ma for younger post-tectonic phases of the batholith. The similarity of these ages with those of volcanism led these authors to propose that granite–greenstone terranes in the Pilbara Craton represented coeval volcano-plutonic complexes.

McNaughton *et al.* (1988) obtained a date of 3578 ± 2 Ma for gabbroic anorthosite in the Shaw Granitic Complex. Bickle *et al.* (1989) reported Pb–Pb ages of ~2966 Ma for younger granite plutons in the same batholith and Bickle *et al.* (1993) reported Pb–Pb results confirming the ~3450 Ma age of a major component of the batholith and identifying a minor component at 3338 ± 52 Ma. The North Pole Monzogranite, which intrudes greenstones 20 km north of the Shaw Granitic Complex, was dated at 3459 + 18 Ma (TIMS U–Pb zircon age) by Thorpe *et al.* (1992).

Models for the evolution of the region were reviewed by Hickman (1981). Critical to these models were geochronological constraints on relationships between the granites and the volcanic successions. Pidgeon (1984) reported U–Pb zircon ages for the Boobina and Spinaway Porphyries of 3307 ± 19 and 2768 ± 16 Ma, respectively. The Boobina Porphyry intrudes greenstones of the upper Warrawoona Group, and the Spinaway Porphyry intrudes lower units of the unconformably overlying volcanic and sedimentary rocks of the Fortescue Group. Barley & De Laeter (1984) reported a Rb–Sr whole-rock age of 3471 ± 125 Ma for volcanic rocks equivalent to the Duffer Formation, and De Laeter & Martyn (1986) reported a Rb–Sr whole-rock age of 3234 ± 117 Ma for molybdenum–copper mineralisation at Coppins Gap. McCulloch *et al.* (1983) obtained Sm–Nd model ages of 3430 and 3400 Ma for felsic volcanic rocks of the Duffer Formation.

Thorpe *et al.* (1992) published the results of a comprehensive isotope dilution TIMS U–Pb zircon investigation, conducted at the Geological Survey of Canada, of Archean felsic units in the Marble Bar region. They found that felsic volcanic rocks of the Warrawoona Group, from the Duffer Formation upwards but with the exception of the Wyman Formation, were deposited in a restricted time period between 3471 and 3449 Ma. U–Pb zircon results from the Wyman Formation defined an age of 3325 ± 3 Ma, indicating a younger volcanic episode. Horwitz & Pidgeon (1993) reported a zircon age of 3.1 Ga for a tuff from the Sholl Belt in the west Pilbara, demonstrating that these volcanic rocks were distinctly younger than volcanic rocks of the Marble Bar region. The SHRIMP U–Pb zircon age of 3515 ± 3 Ma for volcanic rocks of the Coucal Formation of the Warrawoona Group (Buick *et al.* 1995) is the oldest age reported so far for volcanism in the Pilbara Craton.

In a major contribution, Alec Trendall applied SHRIMP zircon geochronology to establish the age of the banded iron-formations of the Hamersley Group of the Mt Bruce Supergroup, which overlies granite–greenstone basement of the Pilbara Craton (Trendall *et al.* 1998). This work demonstrated continuous deposition in the Fortescue and Hamersley Basins for at least 325 million years, from 2775 to 2450 Ma (Trendall & Blockley 2004).

Dating the world's oldest fossils and oldest terrestrial impacts

Stromatolites in cherts of the Dresser Formation of the Warrawoona Group are the world's oldest known fossils (Walter *et al.* 1980; Van Kranendonk *et al.* 2008). The Dresser Formation underlies the Duffer Formation, for which TIMS U–Pb analyses of zircon from two localities indicated upper intercept dates of 3471 ± 5 Ma and 3465 ± 3 Ma (Thorpe *et al.* 1992). These results represent a minimum age for the fossils. SHRIMP analysis of detrital zircons from a felsic volcaniclastic sandstone in the lower chert–barite unit of the Dresser Formation defined a dominant 3525 Ma age component. However one concordant grain has a ^{207}Pb/^{206}Pb date of 3481 ± 3 Ma, which is interpreted as a maximum age for deposition of the Dresser Formation and for the stromatolites (Wingate *et al.* 2009).

The Antarctic Creek Member of the Mt Ada Basalt, which lies beneath the Duffer Formation but above the Dresser formation, is notable for containing spherule-bearing layers that represent the world's oldest recognised terrestrial impacts (Lowe & Byerly 1986; Glikson *et al.* 2004). Byerly *et al.* (2002) reported a SHRIMP date of 3470 ± 2 Ma for euhedral zircons from the Antarctic Creek Member spherule-bearing unit, which agrees within uncertainty with the age of the Duffer Formation. They interpreted the zircons as detrital grains derived locally from coeval or slightly older felsic igneous rocks rather than as material from the impact target and considered the date to approximate the depositional age of the cherts. Most remarkably, Byerly *et al.* (2002) obtained an identical result for a comparable spherule-bearing layer in the Barberton greenstone belt in South Africa.

Hf isotopes in Jack Hills zircons

The application of the ^{176}Lu–^{176}Hf decay system to ancient detrital zircons from the Jack Hills as a means of investigating the earliest processes on Earth is another recent development in the application of geochronological techniques to the Western Australian Archean. Hafnium, as Hf^{4+}, and zirconium, as Zr^{4+}, have very similar ionic radii (0.84 and 0.83 Å, respectively), hence hafnium is a significant component in zircon (typically up to 2% in granitic zircons). Lu is also present in zircon, but only at the ppm level, so the radiogenic ^{176}Hf in zircon closely represents the Hf isotopic composition of the source magma. Studying this system in the ancient Jack Hills zircons provides information on the nature of the Hadean parent magmas.

The first investigation of Hf isotopes in the ancient zircons, by Amelin *et al.* (1999), reported the analyses of 37 zircons from Jack Hills conglomerate sample W74. They concluded that no zircons showed any evidence of an early depleted mantle and that the crust was a significant age when the zircons grew. In contrast, Harrison *et al.* (2005) and Blichert-Toft & Albarède (2008) reported Hf results that indicated a widespread depleted mantle. However, Kemp *et al.* (2010), from a combined Hf and Pb study of 68 Jack Hills zircons, found no evidence in support of a strongly depleted Hadean mantle, in agreement with Amelin *et al.* (1999). They interpreted their data to suggest that Hadean source reservoirs generated granitic magmas throughout the Archean, supporting the notion of a long-lived and globally extensive Hadean protocrust that may have comprised the nuclei of some Archean cratons (Kemp *et al.* 2010).

Geochronological framework of the Pilbara and Yilgarn Cratons

Owing to the constraints of this review, only a brief summary can be made here of the geochronological knowledge of the Archean cratons of Western Australia. Readers interested in the detailed geochronology are referred to recent overviews of the geological history of the Yilgarn Craton (Kositcin *et al.* 2008; Wyche *et al.* 2012; Van Kranendonk *et al.* 2010, 2013) and the Pilbara Craton (Hickman & Van Kranendonk 2012a, b).

The exposed Pilbara Craton (Figure 1) has been divided into five granite–greenstone terranes (East Pilbara Terrane, West Pilbara Superterrane, comprising the Regal, Karratha and Sholl Terranes, and the Kurrana Terrane) and five principal volcanosedimentary basins (Hickman & Van Kranendonk 2012a, b). The extensive U–Pb zircon dataset now available for Pilbara rocks has resulted in closely controlled geochronological correlation of volcanic and granitic activity within the craton. Granite–greenstones in the Pilbara terranes have been dated at 3.52 to 3.07 Ga, formation of basins from 3.02 to 2.93 Ga, and post-orogenic granites from 2.89 to 2.83 Ga. The overlying Fortescue, Hamersley and Turee Creek Groups represent a 2.78–2.42 Ga succession of interbedded clastic and chemical sedimentary and volcanic rocks (Hickman & Van Kranendonk 2012a, b).

The Yilgarn Craton (Figure 1) is divided into the South West, Youanmi and Narryer Terranes and the Eastern Goldfields Superterrane (Cassidy *et al.* 2006). The Narryer Terrane contains the oldest rocks in the craton (>3.7 Ga), and the ~3.0 Ga quartzitic metasedimentary rocks at Mt Narryer and the Jack Hills contain detrital zircons with ages from 4.37 to 3.90 Ga. The Youanmi Terrane is divided into the Murchison and Southern Cross Domains, and includes ~3.0 and 2.8–2.7 Ga greenstone belts within vast areas of 2.8–2.6 Ga granitoids. In the Southern Cross Domain, quartzitic metasedimentary rocks in the Gum Creek, Maynard Hills and Illaara Greenstone Belts (Fig. 1) contain zircons with ages from 4.35 to 3.90 Ga (Wyche *et al.* 2004). The South West Terrane also has ~3.0 and 2.7 Ga greenstone belts isolated within vast areas of 2.7–2.6 Ga granites. However, the ~3.0 Ga quartzitic metasedimentary rocks do not contain detrital zircons older than 3.6 Ga (Pidgeon *et al.* 2010).

In the Eastern Goldfields Superterrane (Fig. 1), which includes the Kalgoorlie, Kurnalpi, Burtville, and Yamarna Terranes, four main periods of volcanism and granite emplacement have been recognised at 2970–2910, 2815–2800, 2775–2735 and 2715–2620 Ma (Pawley *et al.* 2012; Wyche *et al.* 2012). Mole *et al.* (2012) reported patterns of granite formation ages in the southern Yilgarn Craton, highlighting distinct periods of granite formation followed by quiescence from ~3.0 to 2.6 Ga. The ages broadly decrease from west to east and appear to follow a pattern of progressively increasing activity culminating in a final, voluminous granite magmatic event at 2650 to 2620 Ma (Mole *et al.* 2012). The eastern Yilgarn Craton exhibits younger Nd model ages compared to those in terranes west of the Ida Fault, indicating that the crust forming the Eastern Goldfields Superterrane is younger and significantly more juvenile than the western Yilgarn Craton, which comprises older, reworked crust (Champion & Cassidy 2007; Wyche *et al.* 2012; Mole *et al.* 2013). This has profound implications for mineral exploration and is an exceptional outcome underpinning the value of building regional datasets of Nd and other isotopes, such as Lu–Hf (Kirkland *et al.* 2011).

Future isotopic dating studies of Archean cratons of Western Australia

The immediate future of geochronological studies of the Archean rocks of Western Australia will see an expansion of the regional zircon U–Pb dataset, to refine the geochronological framework of the cratons and focus on specific problems of ore genesis or tectonic boundaries. There will also be further studies of the old rocks and old zircons to elucidate the Hadean history of the Yilgarn Craton and of the Earth itself. Recent SHRIMP dating by Tony Kemp at UWA obtained a unimodal 3752 Ma zircon age for a well-preserved meta-anorthosite of the Manfred Complex near Mt Narryer (Tony Kemp pers. comm. 2013), now the oldest known rock in Australia.

More emphasis will be directed towards dating the mafic components of greenstone belts, following the recognition that many mafic intrusive rocks can be dated successfully using zircons found in felsic differentiates, or using baddeleyite (ZrO_2) in coarse-grained, weakly or non-metamorphosed gabbro or dolerite (Wingate 1999). This approach has identified suites of large, ~2.8 Ga mafic-ultramafic intrusions that make up to 40% by volume of greenstones in the northern Murchison Domain and host important V and PGE mineralisation (Ivanic *et al.* 2010). Similar ages for gabbros in the Southern Cross Domain (Wingate *et al.* 2011) and Burtville Terrane (Pawley *et al.* 2012), suggest the possibility of a 2.8 Ga Yilgarn-wide event, but no significant mafic rocks of this age have so far been found in the intervening Kalgoorlie or Kurnalpi Terranes.

New studies by Ian Campbell, Yuri Amelin, and students at ANU are following up SHRIMP or laser-ablation ICPMS U–Pb analyses with chemical abrasion and ultra-high-precision TIMS analyses of the same zircons, to address the need for the extreme time resolution (sub-million-year precision: Amelin & Davis 2006) necessary to understand greenstone belt evolution and solve stratigraphic issues in the Eastern Goldfields, where many events—including mineralisation—occurred in only a few million years. TIMS U–Pb geochronology is currently undergoing a resurgence in Perth, thanks to renewed interest by Steve Denyzsyn (UWA), Alexander Nemchin (Curtin) and GSWA.

With the increasing spatial coverage of the zircon U–Pb database, further studies of patterns and regional trends of ages, inherited components, Th/U ratios, and radiation damage will provide key information on the thermal history and deep structure of the cratons. The database also includes Sm–Nd, Lu–Hf, Pb, Ar–Ar and Rb–Sr datasets, as well as stable isotopes such as oxygen and lithium, and all of these will play an increasing role in developing our geological understanding. As demonstrated so convincingly by the Nd results (Champion & Cassidy 2007; Wyche *et al.* 2012; Mole *et al.* 2013), patterns in the geochronological data, possibly combined with geochemistry and geophysics datasets, have the potential to elucidate the history of the Archean cratons and identify the oldest fragments of the Earth's crust, and to resolve their evolution in space and time.

CONCLUSIONS

In this brief review, we have followed the emergence of geochronology as a key discipline in our understanding of the Archean geology of Western Australia, from the early pioneering efforts of Jeffery and his group at UWA in the 1950s to the highly efficient field-integrated program of SHRIMP-based U–Pb zircon dating currently undertaken by GSWA. Since the 1950s there have been immense changes in the instrumentation and techniques applied to geochronology and this technological evolution is continuing today with new developments in mass spectrometry, micro-crystallography, and laser and ion microprobes. The development of new instrumentation has been accompanied by the evolution of ideas and applications of geochronological systems. The great breakthrough in the development of Rb–Sr whole-rock dating in the 1950s has now been superseded by the application of U–Pb zircon geochronology in the 1990s.

In Australia at least, TIMS geochronology was largely supplanted by the expansion of SHRIMP-based dating in the 1980s and 90s. This has removed the need for highly demanding isotope dilution chemistry and opened up geochronology to all geologists, whereas before, the demands of the technology required that many exponents were analytically trained physicists and chemists. However, isotope-dilution TIMS remains an essential complement to micro-analytical methods, and is still the best technique for high-precision analysis of homogeneous minerals.

It is fair to say that the value of geochronology in solving problems of Archean correlations, in elucidating crustal evolution, and in placing mineral systems in tectonic settings, was not well appreciated by government and industry geologists up until the 1980s, except by a few outstanding individuals such as Alan Wilson and Alec Trendall. This has now changed and we look forward to new developments in technology and new ideas in the application of geochronology and isotope geology to problems of Archean geology in Western Australia in the years to come.

ACKNOWLEDGEMENTS

We thank William Compston, Ian Fletcher, Arthur Hickman, Chris Kirkland, Malcolm McCulloch, Neal McNaughton and Stephen Wyche for helpful discussions on the history of research into the Archean of Western Australia. We also thank Simon Wilde for a very constructive review. Robert Pidgeon acknowledges research support from Curtin Research and Development. Michael Wingate publishes with permission of the Executive Director of the Geological Survey of Western Australia.

REFERENCES

Aldrich L T, Doak J B & Davis G L 1953. The use of ion exchange columns in mineral analysis of age determination. *American Journal of Science* **251**, 377–387.

Amelin Y V 1998. Geochronology of the Jack Hills detrital zircons by precise U–Pb isotope dilution analysis of crystal fragments. *Chemical Geology* **146**. 25–38.

Amelin Y V & Davis W J 2006. Isotopic analysis of lead in sub-nanogram quantities by TIMS using a ^{202}Pb–^{205}Pb spike. Journal of Analytical and Atomic Spectrometry, 21: 1063–1061.

Amelin Y V, Lee D-C, Halliday A N & Pidgeon R T 1999. Nature of the Earth's earliest crust from hafnium isotopes in single detrital zircons. *Nature* 399, 252–255.

Arriens P A 1971. The Archaean geochronology of Australia. *In:* Glover J E (ed.) *Symposium on Archaean rocks*, pp. 11–23. Geological Society of Australia Special Publication **3**.

Barley M E & De Laeter J R 1984. Disturbed Rb–Sr whole-rock systems of the early Archaean Duffer Formation, Eastern Pilbara Block, Western Australia. *Journal of the Royal Society of Western Australia* 66, 129–134.

Bickle M J, Bettenay L F, Chapman H J, Groves D I, McNaughton N J, Campbell I H & De Laeter J R 1989. The age and origin of younger granitic plutons of the Shaw Batholith in the Archaean Pilbara Block, Western Australia. *Contributions to Mineralogy and Petrology* **101**, 361–376.

Bickle M J, Bettenay L F, Chapman H J, Groves D I, McNaughton N J, Campbell I H & De Laeter J R 1993. Origin of the 3500 Ma – 3300 Ma calc-alkaline rocks in the Pilbara Archaean: isotopic and geochemical constraints. *Precambrian Research* 60, 117–149.

Blichert-Toft J & Albarède F 2008. Hafnium isotopes in Jack Hills zircon and the formation of the Hadean Crust. *Earth and Planetary Science Letters* **265**, 686–702.

Bosch D, Bruguier O & Pidgeon R T 1996. Evolution of an Archaean metamorphic belt: a conventional and SHRIMP U–Pb study of accessory minerals from the Jimperding metamorphic belt, Yilgarn Craton, Western Australia. *Journal of Geology* **104**, 695–711.

Buick R, Thornet J R, McNaughton N J, Smith J B, Barley M E & Savage M 1995. Record of emergent continental crust ~3.5 billion years ago in the Pilbara Craton of Australia. *Nature* **375**, 574–577.

Byerly G R, Lowe D R, Wooden J L & Xie X 2002. An Archean impact layer from the Pilbara and Kaapvaal cratons. *Science* **297**, 1325–1327.

Cassidy K, Champion D, Krapež B, Barley M E, Brown S J A, Blewett R S, Groenewald P B & Tyler I M 2006. A revised geological framework for the Yilgarn Craton, Western Australia. *Geological Survey of Western Australia Record* **2006/8**.

Cavosie A J, Valley J W & Wilde S A 2005. Magmatic δ^{18}O in 4400–3900 Ma detrital zircons: a record of the alteration and recycling of crust in the Early Archean. *Earth and Planetary Science Letters* **235**, 663–681.

Champion D C & Cassidy K F 2007. An overview of the Yilgarn Craton and its crustal evolution. *In:* Bierlein F P & Knox-Robinson C M (eds) *Proceedings of Geoconferences (WA) Inc. Kalgoorlie '07 Conference, 25–27 September 2007, Kalgoorlie Western Australia*, pp.8–13. Geoscience Australia Record **2007/14**.

Clement S W J, Compston W & Newstead G 1977. Design of a large high resolution ion microprobe. *In: Abstract volume of 1st International Conference on Secondary ion Mass Spectrometry, Münster* (published in full as Appendix 1 of Ireland *et al.* 2008).

Claoué-Long J C, Compston W & Cowden A 1988. The age of the Kambalda greenstones resolved by ion-microprobe: implications for Archaean dating methods. *Earth and Planetary Science Letters* 89, 239–259.

Claoué-Long J C, Thirlwall M F & Nesbitt R W 1984. Revised Sm-Nd systematics of Kambalda greenstones, Western Australia. *Nature* 307, 697–701.

Compston W & Jeffery P M 1959. Anomalous "Common Strontium" in granite. *Nature* 184, 1792–1793.

Compston W, Jeffery P M & Riley G H 1960. Age of emplacement of granite. *Nature* **186**, 702–703.

Compston W & Arriens P A 1968. The Precambrian geochronology of Australia. *Canadian Journal of Earth Sciences* **5**, 561–583.

Compston W & Pidgeon R T 1986. Jack Hills, evidence of more very old detrital zircons in Western Australia. *Nature* **321**, 766–769.

Crowley J L, Myers J S, Sylvester P J & Cox R A 2005. Detrital zircon from the Jack Hills and Mount Narryer, Western Australia: evidence for diverse >4.0 Ga source rocks. *Journal of Geology* **113**, 239–263.

De Laeter J R 1994. A question of time: Royal Society Medallist's Lecture for 1993. *Journal of the Royal Society of Western Australia* 77, 5–14.

De Laeter J R & Baxter J L 1987. Rb–Sr geochronology of granitoids from Mount Mulgine, Western Australia. *Journal of the Royal Society of Western Australia* 69, 113–116.

De Laeter J R & Blockley J G 1972. Granite ages within the Archean Pilbara Block. *Journal of the Geological Society of Australia* **19**, 363–370.

De Laeter J R, Fletcher I R, Bickle M J, Myers J S, Libby W G & Williams I R 1985. Rb–Sr, Sm–Nd and Pb–Pb geochronology of the ancient gneisses from Mount Narryer, Western Australia. *Australian Journal of Earth Sciences* **32**, 349–358.

De Laeter J R, Fletcher I R, Rosman K J R, Williams I R, Gee R D. & Libby W G 1981a. Early Archaean gneisses from the Yilgarn Block, Western Australia. *Nature* **292**, 322–324.

De Laeter J R & Kennedy A K 1998. A double focusing mass spectrometer for geochronology. *International Journal of Mass Spectrometry* **178**, 43–50.

De Laeter J R, Lewis J D & Blockley J G 1975. Granite ages within the Shaw Batholith of the Pilbara Block. *Geological Survey of Western Australia Annual Report for 1974*, 73–79.

De Laeter J R, Libby W G & Trendall A F 1981b. The older Precambrian geochronology of Western Australia. *In:* Glover

J E & Groves D I (eds) *Archaean geology: Proceedings Second International Symposium, Perth 1980*, pp. 145–157. Geological Society of Australia Special Publication **7**.

De Laeter J R & Martyn J E 1986. Age of the molybdenum–copper mineralization at Coppin Gap, Western Australia. *Australian Journal of Earth Sciences* **33**, 65–71.

De Laeter J R & Trendall A F 1970. The age of the Copper Hills porphyry. *Geological Survey of Western Australia Annual Report for 1969*, 54–59.

De Laeter J R & Trendall A F 1979. The contribution of geochronology to Precambrian studies of Western Australia. *Journal of the Royal Society of Western Australia* **62**, 21–31.

De Laeter J R & Trendall A F 2002. The oldest rocks: the Western Australian connection. *Journal of the Royal Society of Western Australia* **85**, 153–160.

Dunn S J, Nemchin A A, Cawood P A & Pidgeon R T 2005. Provenance record of the Jack Hills metasedimentary belt: source of the Earth's oldest zircons. *Precambrian Research* **138**, 235–254.

Dunphy J M, Fletcher I R, Cassidy K E & Champion D C 2003. Compilation of SHRIMP U–Pb geochronology data, Yilgarn Craton, Western Australia, 2001–2002. *Geoscience Australia Record* **2003/15**.

Fletcher I R, Dunphy J M, Cassidy K F & Champion D C 2001. Compilation of SHRIMP U–Pb geochronological data, Yilgarn Craton, Western Australia, 2000–2001. *Geoscience Australia Record* **2001/47**.

Fletcher I R & McNaughton N J 2002. Granitoid geochronology: SHRIMP zircon and titanite data. *In:* Cassidy K E, Champion D C, McNaughton N J, Fletcher I R, Whitaker A, Bastrakova I & Budd A R (eds) *Characterisation and metallogenic significance of Archaean Granitoids of the Yilgarn Craton, Western Australia*, pp. 6-1–6.156. Minerals and Energy Research Institute of Western Australia Report **P482**.

Fletcher I R & Rosman K J R 1984. Sm–Nd geochronology of greenstone belts in the Yilgarn Block, Western Australia. *Precambrian Research* **26**, 333–361.

Fletcher I R, Rosman K J R & Libby W G 1988. Sm–Nd, Pb–Pb and Rb–Sr geochronology of the Manfred Complex, Mount Narryer, Western Australia. *Precambrian Research* **38**, 343–354.

Fletcher I R, Wilde S A & Rosman K J R 1985. Sm–Nd model ages across the margins of the Archaean Yilgarn Block, eastern Australia — III. The western margin. *Australian Journal of Earth Sciences* **32**, 73–82.

Fletcher I R, Williams S J, Gee R D & Rosman K J R 1983. Sm–Nd model ages across the margins of the Archaean Yilgarn Block, Western Australia; northwest transect into the Proterozoic Gascoyne Province. *Journal of the Geological Society of Australia* **30**, 167–174.

Froude D O, Ireland T R, Kinny P D, Williams I S, Compston W, Williams I R & Myers J S 1983. Ion microprobe identification of 4100–4200 Myr-old terrestrial zircons. *Nature* **304**, 616–618.

Glikson A Y, Allen C & Vickers J 2004. Multiple 3.47-Ga-old asteroid impact fallout units, Pilbara Craton, Western Australia. *Earth and Planetary Science Letters* **221**, 383–396.

Greenhalgh D & Jeffery P M 1959. A contribution to the pre-Cambrian chronology of Australia. *Geochimica et Cosmochimica Acta* **16**, 39–57

Hamilton P J, Evenson N M, O'Nions R K , Smith H S & Erlank A J 1979. Sm–Nd dating of Onverwacht Group Volcanics, southern Africa. *Nature* 279, 298–300.

Harrison T M, Blichert-toft J, Muller W, Albaréde F, Holden P & Mojzsis S J 2005. Heterogeneous Hadean hafnium: evidence of continental crust at 4.4 to 4.5 Ga. *Science* **310**, 1947–1950.

Hickman A H 1981. Crustal evolution of the Pilbara Block, Western Australia. *In:* Glover J E & Groves D I (eds) *Archaean geology: Proceedings Second International Symposium, Perth 1980*, pp. 57–69. Geological Society of Australia Special Publication **7**.

Hickman A H 1983. Geology of the Pilbara Block and its environs. *Geological Survey of Western Australia Bulletin* **127**.

Hickman A H & Lipple S L 1975. Explanatory Notes on the Marble Bar 1:250 000 Geological Sheet, Western Australia. *Geological Survey of Western Australia Record* **1974/20**.

Hickman A H & Smithies R H in prep. Archean geology of the northwest Pilbara Craton, Western Australia. *Geological Survey of Western Australia Report* **92**.

Hickman A H & Van Kranendonk M J 2012a. Early Earth evolution: evidence from the 3.5–1.8 Ga geological history of the Pilbara region of Western Australia. *Episodes* **35**, 283–297.

Hickman A H & Van Kranendonk M J 2012b. A billion years of Earth history: a geological transect through the Pilbara Craton and the Mount Bruce Supergroup — a field guide to accompany 34th IGC Excursion WA-2. *Geological Survey of Western Australia Record* **2012/10**.

Horwitz R & Pidgeon R T 1993. 3.1 Ga tuff from the Sholl Belt in the west Pilbara: further evidence for diachronous volcanism in the Pilbara Craton of Western Australia. *Precambrian Research* **60**, 175–183.

Ireland T R, Clement S, Compston W, Foster J J, Holden P, Jenkins B, Lanc P, Schram N & Williams I S 2008. Development of SHRIMP. *Australian Journal of Earth Sciences* **55**, 937–954.

Ivanic T J, Wingate M T D, Kirkland C L, Van Kranendonk M J & Wyche S 2010. Age and significance of voluminous 2815–2715 Ma layered mafic–ultramafic intrusions in the Murchison Domain, Yilgarn Craton. *Australian Journal of Earth Sciences* **57**, 597–614.

Kemp A I S, Wilde S A, Hawkesworth C J, Coath C D, Nemchin A A & Pidgeon R T 2010. Hadean crustal evolution revisited: new constraints from Pb-Hf systematics of the Jack Hills zircons. *Earth and Planetary Science Letters* **296**, 45–56.

Kinny P D 1990. Age spectrum of detrital zircons in the Windmill Hill Quartzite. *In:* Ho S E, Glover J E, Myers J S & Muhling J R (eds) *3rd International Archaean symposium, Excursion Guide Book*, pp. 116–117. Geology Department and University Extension, University of Western Australia Publication **21**.

Kinny P D & Nutman A P 1996. Zirconology of the Meeberrie Gneiss, Yilgarn Craton, Western Australia: an early Archaean migmatite. *Precambrian Research* **78**, 165–178.

Kinny P D, Williams I S, Froude D O, Ireland T R & Compston W 1988. Early Archaean zircon ages from orthogneiss and anorthosites at Mount Narryer, Western Australia. *Precambrian Research* **38**, 325–341.

Kirkland C L, Spaggiari C V, Wingate M T D, Smithies R H, Belousova E A, Murphy R & Pawley M J 2011. Inferences on crust–mantle interaction from Lu–Hf isotopes: a case study from the Albany–Fraser Orogen. *Geological Survey of Western Australia Record* **2011/12**.

Kirkland C L & Wingate M T D 2013. Reading deep time: radiogenic isotope geochronology. *Geological Survey of Western Australia Record* **2012/15**.

Kositcin N, Brown S J A, Barley M E, Krapež B, Cassidy K F & Champion D C 2008. SHRIMP U–Pb zircon age constraints on the Late Archaean tectonostratigraphic architecture of the Eastern Goldfields Superterrane, Yilgarn Craton, Western Australia. *Precambrian Research* **161**, 5–33.

Kober B, Pidgeon R T & Lippolt H J 1989. Single-zircon dating by stepwise Pb-evaporation determines the Archaean history of detrital zircons from the Jack Hills, Western Australia. *Earth and Planetary Science Letters* **91**, 286–296.

Leggo P J, Compston W & Trendall A F 1965. Radiometric ages of some Precambrian rocks from the Northwest Division of Western Australia. *Journal of the Geological Society of Australia* **12**, 53–65.

Lowe D R & Byerly G R 1986. Early Archean silicate spherules of probable impact origin, South Africa and Western Australia, *Geology* **14**, 83–86.

Maas R & McCulloch M T 1991. The provenance of Archaean clastic metasediments in the Narryer Gneiss Complex, Western Australia: trace element geochemistry, Nd isotopes, and U–Pb ages for detrital zircons. *Geochimica et Cosmochimica Acta* **55**, 1914–1932.

McCulloch M T & Compston W 1981. Sm–Nd age of Kambalda and Kanowna greenstones and heterogeneity in the Archaean mantle. *Nature* **294**, 322–327.

McCulloch M T, Collerson K D & Compston W 1983b. Growth of Archaean crust within the Yilgarn Block, Western Australia. *Journal of the Geological Society of Australia* **30**, 155–160.

McCulloch M T, Compston W & Froude D 1983a. Sm–Nd and Rb–Sr dating of Archaean gneisses, Eastern Yilgarn Block, Western Australia. *Journal of the Geological Society of Australia* **30**, 149–153.

McNaughton N J & Bickle M J 1987. K–feldspar Pb–Pb isotope systematics of Archaean post–kinematic granitoid intrusions of the Diemals area, central Yilgarn Block. *Chemical Geology* **66**, 193–208.

McNaughton N J & Cassidy K F 1990. The age of the Liberty Granodiorite: a reassessment of the broad synchroneity of mesothermal gold mineralization within the Norseman–Wiluna Belt, Western Australia. *Australian Journal of Earth Sciences* 37, 373–376.

McNaughton N J, Green M D, Compston W & Williams I S 1988. Are anorthositic rocks basement to the Pilbara Craton? *Geological Society of Australia Abstracts* **21**: 272–273.

McNaughton N J & Groves D I 1996. A review of Pb-isotope constraints on the genesis of lode-gold deposits in the Yilgarn Craton, Western Australia. *Journal of the Royal Society of Western Australia* 79, 123–129.

Mojzsis S J, Harrison T M & Pidgeon R T 2001. Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4300 Ma ago. *Nature* 409, 178–181.

Mole D R, Fiorentini M L, Thebaud N, McCuaig T C, Cassidy K F, Kirkland C L, Wingate M T D, Romano S S, Doublier M P & Belousova E A 2012. Spatio-temporal constraints on lithospheric development in the southwest-central Yilgarn Craton, Western Australia. *Australian Journal of Earth Sciences* **59**, 625–656.

Mole D R, Fiorentini M L, Cassidy K F, Kirkland C L, Thebaud N, McCuaig T C, Doublier M P, Duuring P, Romano S S, Maas R, Belousova E A, Barnes S J & Miller J 2013. Crustal evolution, intra-cratonic architecture and the metallogeny of an Archaean craton. *In:* Jenkin G R T, Lusty P A J, McDonald I, Smith M P, Boyce A J & Wilkinson J J (eds) *Ore deposits in an evolving Earth*. Geological Society of London Special Publication 393. doi:10.1144/SP393.8

Muhling P C & De Laeter J R 1971. Ages of granitic rocks in the Poona–Dalgaranga area of the Yilgarn Block, Western Australia. *In:* Glover J E (ed.) *Symposium on Archaean rocks*, pp. 25–31. Geological Society of Australia Special Publication 3.

Myers J S & Williams I R 1985. Early Precambrian crustal evolution at Mount Narryer, Western Australia. *Precambrian Research* 27, 153–163.

Nelson D R 1995. Compilation of SHRIMP U–Pb zircon geochronology data, 1994. *Geological Survey of Western Australia Record* **1995/3**.

Nelson D R 1996. 105007: leucocratic orthogneiss, Churla Well. *Geological Survey of Western Australia Geochronology Record* **12**.

Nelson D R 1997a. Compilation of SHRIMP U–Pb zircon geochronology data, 1996. *Geological Survey of Western Australia Record* **1997/2**.

Nelson D R 1997b. Evolution of the Archaean granite–greenstone terranes of the Eastern Goldfields, Western Australia: SHRIMP U–Pb zircon constraints. *Precambrian Research* 83, 57–81.

Nelson D R 1997c. 105007: leucocratic orthogneiss, Churla Well. *Geological Survey of Western Australia Geochronology Record* **13**.

Nelson D R 2005. 178064: coarse sandstone, The Stock Well. *Geological Survey of Western Australia Geochronology Record* **591**.

Nelson D R, Robinson B W & Myers J S 2000. Complex geological histories extending for ≥ 4.0 Ga deciphered from xenocryst zircon microstructures. *Earth and Planetary Science Letters* 181, 89–102.

Nemchin A A & Pidgeon R T 1997. Evolution of the Darling Range Batholith, Yilgarn Craton, Western Australia: a SHRIMP zircon study. *Journal of Petrology* 38, 625–649.

Nieuwland D A & Compston W 1981. Crustal evolution in the Yilgarn Block near Perth, Western Australia. *In:* Glover J E & Groves D I (eds) *Archaean geology: Proceedings Second International Symposium, Perth 1980*, pp. 159–171. Geological Society of Australia Special Publication 7.

Nutman A P, Bennett V C, Kinny P D & Price R 1993. Large-scale crustal structure of the Northwestern Yilgarn Craton, Western Australia: evidence from Nd isotopic data and zircon geochronology. *Tectonics* 12, 971–981.

Nutman A P, Kinny P D, Compston W & Williams I S 1991. SHRIMP U–Pb zircon geochronology of the Narryer Gneiss Complex, Western Australia. *Precambrian Research* 52, 275–300.

Oversby V M 1975. Lead isotope systematics and ages of Archaean acid intrusives in the Kalgoorlie–Norsemen area, Western Australia. *Geochimica et Cosmochimica Acta* 39, 1107–1125.

Oversby V M 1976. Isotopic ages and geochemistry of Archaean acid igneous rocks from the Pilbara, Western Australia. *Geochimica et Cosmochimica Acta* 40, 817–829.

Pawley M J, Wingate M T D, Kirkland C L, Wyche S, Hall C E, Romano S S & Doublier M P 2012. Adding pieces to the puzzle: episodic crustal growth and a new terrane in the northeast Yilgarn Craton, Western Australia. *Australian Journal of Earth Sciences* 59, 603–623.

Peck W H, Valley J W, Wilde S A & Graham C M 2001. Oxygen isotope ratios and rare earth elements in 3.3 to 4.4 Ga zircons: ion microprobe evidence for high δ^{18}O continental crust and oceans in the Early Archean. *Geochimica et Cosmochimica Acta* 65, 4215–4229.

Perring C S & McNaughton N J 1990. Proterozoic remobilization of ore metals within Archaean gold deposits: lead isotope evidence from Norseman, Western Australia. *Australian Journal of Earth Sciences* 37, 369–372.

Perring C S & McNaughton N J 1992. The relationship between Archaean gold mineralization and spatially associated minor intrusives at the Kambalda and Norseman gold camps, Western Australia: lead isotope evidence. *Mineralium Deposita* 27, 10–22.

Pidgeon R T 1978a. 3450 M.Y. old volcanics in the Archaean layered greenstone succession of the Pilbara Block, Western Australia. *Earth and Planetary Science Letters* 37, 421–428.

Pidgeon R T 1978b. Geochronological investigation of granite batholiths of the Archaean granite–greenstone terrain of the Pilbara Block, Western Australia. *In:* Smith I E M & Williams J G (eds) *Proceedings of the 1978 Archaean Geochemistry Conference*, pp. 360–362. University Toronto Press, Toronto.

Pidgeon R T 1984. Geochronological constraints on early volcanic evolution of the Pilbara Block, Western Australia. *Australian Journal of Earth Sciences* **31**, 237–242.

Pidgeon R T & Hallberg J A 2000. Age relationships in supracrustal sequences in the northern part of the Murchison Terrane, Archaean Yilgarn Craton, Western Australia: a combined field and zircon U–Pb study. *Australian Journal of Earth Sciences* 47, 153–165.

Pidgeon R T & Nemchin A A 2006. High abundance of early Archaean grains and the age distribution of detrital zircons in a sillimanite-bearing quartzite from Mount Narryer, Western Australia. *Precambrian Research* **150**, 201–220.

Pidgeon R T & Wilde S A 1990. The distribution of 3.0 and 2.7 Ga volcanic episodes in the Yilgarn Craton of Western Australia. *Precambrian Research* 48, 309–325.

Pidgeon R T & Wilde S A 1998. The interpretation of complex zircon U–Pb systems in Archaean granitoids and gneisses from the Jack Hills, Narryer Gneiss Terrane, Western Australia. *Precambrian Research* 91, 309–332.

Pidgeon R T, Wilde S A, Compston W & Shield M W 1990. Archaean evolution of the Wongan Hills Greenstone Belt, Yilgarn Craton, Western Australia. *Australian Journal of Earth Sciences* **37**, 279–292.

Pidgeon R T, Wingate M T D, Bodorkos S & Nelson D R 2010. The age distribution of detrital zircons in quartzites from the Toodyay–Lake Grace Domain, Western Australia: implications for the early evolution of the Yilgarn Craton. *American Journal of Science* **310**, 1115–1135.

Richards J R, Fletcher I R & Blockley J G 1981. Pilbara galenas: precise isotopic assay of the oldest Australian leads; model ages and growth-curve implications. *Mineralium Deposita* **16**, 7–30.

Roddick J C 1984. Emplacement and metamorphism of Archaean mafic volcanics at Kambalda, Western Australia – geochemical and isotopic constraints. *Geochimica et Cosmochimica Acta* **48**, 1305–1318.

Sangster D F & Brook W A 1977. Primitive lead in an Australian Zn–Pb–Ba deposit. *Nature* **270**, 423.

Schärer U & Allègre C J 1985. Determination of the age of the Australian continent by single grain analysis of Mount Narryer metaquartzite. *Nature* **315**, 52–55.

Schiøtte L & Campbell I H 1996. Chronology of Mount Magnet granite–greenstone terrain, Yilgarn Craton, Western Australia: implications for field based predictions of the relative timing of granitoid emplacement. *Precambrian Research* **78**, 237–260.

Sircombe K N, Cassidy K F, Champion D C & Tripp G 2007. Compilation of SHRIMP U–Pb geochronological data, Yilgarn Craton, Western Australia, 2004–2006. *Geoscience Australia Record* **2007/01.**

Stacey J S & Kramers J D 1975. Approximation of terrestrial lead isotope evolution by a two stage model. *Earth and Planetary Science Letters* **26**, 207–221.

Thern R E & Nelson D R 2012. Detrital zircon age structure within ca. 3 Ga metasedimentary rocks, Yilgarn Craton: elucidation of Hadean source terranes by principal component analysis. *Precambrian Research* **214**, 28–43.

Thorpe R I, Hickman A H, Davis D W, Mortensen J K & Trendall A F 1992. U–Pb zircon geochronology of Archaean felsic units in the Marble Bar region, Pilbara Craton, Western Australia. *Precambrian Research* **56**, 169–189.

Tilton G R, Patterson C, Brown H, Inghram M, Hayden R, Hess D & Larsen E 1955. Isotopic composition and distribution of lead, uranium and thorium in a Precambrian granite. *Bulletin of the Geological Society of America* 66, 1131–1148.

Trendall A F & Blockley J D 2004. Precambrian iron-formations. *In:* Erikson P G, Altermann W, Nelson D R, Mueller W U & Catuneanu O (eds) *The Precambrian Earth: tempos and events in Precambrian time (Developments in Precambrian Geology 12)*, pp. 403–421. Elsevier, Amsterdam.

Trendall A F, Nelson D R, De Laeter J R. & Hassler S W 1998. Precise zircon U–Pb ages from the Marra Mamba Iron Formation and the Wittenoom Formation, Hamersley Group, Western Australia. *Australian Journal of Earth Sciences* **45**, 137–142.

Turek A 1966. Rubidium–strontium isotopic studies in the Kalgoorlie–Norseman area, Western Australia. PhD thesis, Australian National University, Canberra (unpubl.).

Valley J W, Peck W H, King E M & Wilde S A 2002. A cool early Earth. *Geology* 30, 351–354.

Van Kranendonk M J, Ivanic T J, Wyche S, Wilde S A & Zibra I 2010. A time transect through the Hadean to Neoarchean geology of the western Yilgarn Craton — a field guide. *Geological Survey of Western Australia Record* **2010/19.**

Van Kranendonk M J, Ivanic T J, Wingate M T D, Kirkland C L & Wyche S 2013. Long–lived, autochthonous development of the Archean Murchison Domain, and implications for Yilgarn Craton tectonics. *Precambrian Research* **229**, 49–92.

Van Kranendonk M J, Philippot P, Lepot K, Bodorkos S & Pirajno F 2008. Geological setting of Earth's oldest fossils in the ca. 3.5 Ga Dresser Formation, Pilbara Craton, Western Australia. *Precambrian Research* **167**, 93–124.

Walter M R, Buick R & Dunlop J S R 1980. Stromatolites, 3,400–3,500 Myr old from the North Pole area, Western Australia. *Nature* **284**, 443–445.

Wang Q 1998. Geochronology of the granite–greenstone terranes in the Murchison and Southern Cross provinces of the Yilgarn Craton, Western Australia. PhD thesis, Australian National University, Canberra (unpubl.).

Wasserburg G J 1954. Argon40/potassium40 dating. *In:* Faul H (ed.) *Nuclear Geology*, pp. 341–349. Wiley and Sons, New York.

Wiedenbeck M & Watkins K P 1993. A time scale for granitoid emplacement in the Archaean Murchison Province, Western Australia, by single zircon geochronology. *Precambrian Research* **61**, 1–26.

Wijbrans J R & McDougall I 1987. On the metamorphic history of an Archaean granitoid greenstone terrain, East Pilbara, Western Australia, using the ^{40}Ar/^{39}Ar age spectrum method. *Earth and Planetary Science Letters* **84**, 226–242.

Wilde S A & Pidgeon R T 1986. Geology and geochronology of the Saddleback Greenstone belt in the Archaean Yilgarn Block, southwestern Australia. *Australian Journal of Earth Sciences* **33**, 491–501.

Wilde S A & Spaggiari C V 2007. The Narryer Terrane, Western Australia: a review. *In:* Van Kranendonk M J, Smithies R H & Bennett V C (eds) *Earth's oldest rocks (Developments in Precambrian Geology 15)*, pp. 275–304. Elsevier, Amsterdam.

Wilde S A, Valley J W, Peck W H & Graham C M 2001. Evidence from detrital zircons for the existence of continental crust and oceans on Earth 4.4 Gyr ago. *Nature* 409, 175–177.

Wilson A F, Compston W, Jeffery P M & Riley G H 1960. Radioactive ages from the Precambrian rocks in Australia. *Journal of the Geological Society of Australia* **6**, 179–195.

Williams I S & Collins W J 1990. Granite–greenstone terranes in the Pilbara Block, Western Australia, as coeval volcanic-plutonic complexes: evidence from U–Pb zircon dating of the Mount Edgar Batholith. *Earth and Planetary Science Letters* **97**, 41–53.

Wingate M T D 1999. Ion microprobe baddeleyite and zircon ages for late Archean mafic dykes of the Pilbara Craton, Western Australia. *Australian Journal of Earth Sciences* **46**, 493–500.

Wingate M T D, Bodorkos S & Van Kranendonk, M J 2009. 180070: volcaniclastic sandstone, drillcore PDP2c, Dresser Mine. *Geological Survey of Western Australia Geochronology Record* **811**.

Wingate M T D, Kirkland C L, Riganti A & Wyche S 2011. 185990: metagabbro, Grass Flat Bore. *Geological Survey of Western Australia Geochronology Record* **868**.

Wyche S, Nelson D R & Riganti A 2004. 4350–3130 Ma detrital zircons in the Southern Cross Granite–Greenstone Terrane, Western Australia: implications for the early evolution of the Yilgarn Craton. *Australian Journal of Earth Sciences* **51**, 31–45.

Wyche S, Kirkland C L, Riganti A, Pawley M J, Belousova E & Wingate M T D 2012. Isotopic constraints on stratigraphy in the central and eastern Yilgarn Craton, Western Australia. *Australian Journal of Earth Sciences* **59**, 657–670.

Received 4 November 2013; accepted 16 January 2014